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A Solid Oxide Fuel Cell (SOFC)-Based Biogas-from-Waste Generation System for Residential Buildings in China: A Feasibility Study

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Abstract: The building sector consumes a great deal of energy and generates organic waste, and thus has been a cause of considerable environmental concern. One distributed-energy technique, solid oxide fuel cell (SOFC)-based biogas-from-waste generation, has shown promise for waste treatment as well as energy saving in buildings. This study proposes a high-efficiency cooling, heating and electricity-generation system with an SOFC-absorption water-cooled tri-generation configuration. Operations data from a typical high-rise commercial building in Shanghai were analyzed as a case study of the proposed system's economic, environmental, and social feasibility in China. The results indicated that its economic performance was satisfactory, with a short payback period of less than one year if subsidized. Additionally, the system was found to achieve high efficiency: i.e., 85%, as compared to approximately 40% achieved by conventional combustion-powered systems. Finally, in terms of social feasibility, survey respondents not only expressed positive overall attitudes towards the application of the system, but also raised concerns about its long-term operating costs. Given that foreseeable technological advancements promise greater flexibility and reduced space requirements, these results imply that the proposed integrated SOFC multi-generation system will be well-suited to future infrastructure and building projects in China.

Keywords: distributed-energy resources; distributed waste-treatment systems; building waste to energy

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1. Introduction

The environmental impacts of the building sector can be divided into two broad categories: (1) waste production, and (2) energy consumption. The occupants of completed buildings produce abundant waste, of which organic waste (e.g., food scraps and sewage) comprises 40% in China [1]. China is the world's largest energy consumer now. The global net primary energy consumption grew by 2.5% in 2011, and China alone contributed 71% of the global energy consumption increment [2]. In China, building energy consumption accounts for 46.7% of the total society energy consumption, and 60% of the carbon emission in cities comes from maintaining buildings' function [3]. The effective recycling and treatment of organic waste is difficult due to its bacteriological and other health hazards, unpleasant smells, and intricate processing, often at a lengthy geographical distance from its source. Dealing with organic waste from buildings requires effective waste classification, proper recycling procedures, and appropriate treatment methods [4]. In China, the amount of food waste generated per year is approximately 90 million tons, and 98% of all organic waste is treated using unsustainable traditional methods [1]. Such methods are, not only a cause of environmental pollution, but also a waste of this organic material's stored chemical energy. Energy consumption in the construction industry, meanwhile, has been growing rapidly, exceeding that of the transportation and industrial sectors [5], and causing heavy environmental impacts as well as energy shortages and supply problems. In 2016, China's total primary energy consumption reached 4.36 billion tons of standard coal equivalent [6], of which the building sector accounted for 15–16% [6]. In short, it is reasonable to characterize the country's current alarming levels of building-related energy consumption and waste production as a hindrance to its development.

The concept of combining distributed waste treatment (DWT) with distributed energy resources (DER) has been shown to ameliorate both energy consumption and environmental pollution [1]. Such an approach also provides citizens with a means of treating their waste at the source, thus simplifying the treatment procedure and minimizing the pollution caused by transporting waste to distant locations. Biogas generation is an established DWT–DER technique for urban organic waste treatment in China. However, it has suffered from operational issues such as low methane content, high levels of impurities, and instability, especially in relation to food waste [1]. Each of these characteristics limit its fuel efficiency and requires high levels of fuel-flexibility among biogas consumers. To bypass these difficulties, SOFC servers have been proposed as alternative biogas users. A SOFC is an electrochemical-conversion DER device that produces electricity directly from a highly efficient and eco-friendly process of fuel oxidation, and has high fuel-flexibility, high energy efficiency, low environmental impact, and a long lifespan [7–9]. Prior research has found biogas to have great potential as fuel for SOFCs, with energy efficiency of 55–65% or better [10], and that SOFC-based multi-generation systems can achieve higher efficiency (72–90%) than traditional thermal power generators (35–45%) [11], in addition to reducing the emission of greenhouse gases (GHGs) and gaseous pollutants (e.g., NO_x and SO_2) [12].

Unfortunately, there are high costs associated with the current SOFC designs and their degradation over the long timescales needed for commercial application [11]. The demand for cleaner, sustainable, secure and efficient processes for energy conversion drives solid oxide fuel cell (SOFC) research [13]. The present study proposes a SOFC-based multi-generation system for converting food waste into biogas, designed as an integrated energy system for green buildings, with the wider aim of solving the apparent contradiction between the system's high energy consumption and environmental protection. Because little or no research has focused on the application of SOFCs in China, let alone their combination with waste-to-biogas systems, the application of the proposed system in China was deemed a useful topic for investigation. As such, it utilized operations data from a typical high-rise commercial building in Shanghai as a case study of the proposed system's economic, environmental, and social feasibility in China.

2. Proposed System

The proposed application of a new integrated DWT and DER system to buildings (Figure 1) comprises biogas generation and treatment (BGT) as well as SOFC-based multi-generation. The BGT subsystem combines organic-waste collection, biogas generation, and biogas pretreatment via anaerobic digestion (AD) to generate biofuel for the multi-generation subsystem [14], combining syngas-fueled SOFC servers and waste-heat recovery by absorption-cooling chillers and a water-heating system [12,15]. As well as recycling waste heat for cooling and water heating, the multi-generation subsystem is intended to provide buildings with a continuous supply of electricity.

2.1. Biogas Generation and Treatment (BGT)

The process of biogas generation is shown in Figure 1 (A) and the flow of energy multigeneration for buildings is shown in Figure 1 (B).

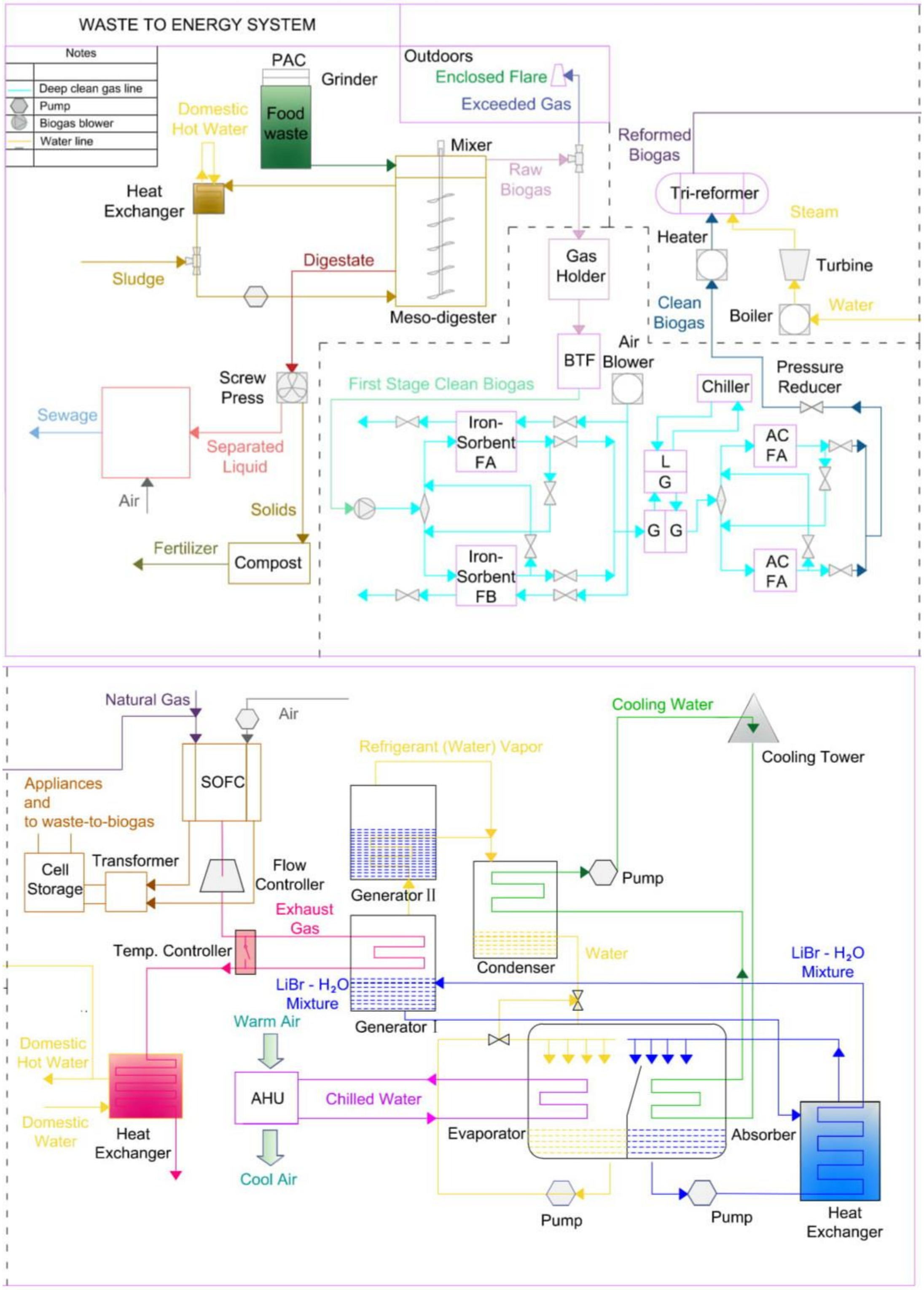

Figure 1. Overview of the Proposed System (adapted from References [12,16–19]).

2.2. SOFC-Based Multi-Generation

Because the DWT–DER system uses biogas, it achieves carbon-neutral power generation, while its biogas digestion plant also serves as a waste-treatment facility. However, the raw biogas that the system initially generates contains several impurities—e.g., sulfur compounds, siloxanes and water

—of which concentrations must be reduced to below the SOFC's tolerance threshold. H_2S, which is highly corrosive, notably to the SOFC's nickel catalyst [20], may be treated so that it becomes oxides of sulfur or sulfuric acid (Equation (1)):

$$SO_X + (1.5 - 0.5x)\,O_2 + H_2O \rightarrow H_2SO_4 \quad (1)$$

The system utilizes Bi-On-Fe for desulphurization. The iron sponge allows a conservative retention time to reduce the concentration of H_2S to less than 0.5 ppm_v (Equations (2) and (3)) [21,22]. The iron-based filters are reusable, if given regular maintenance (Equation (4)).

$$2Fe(OH)_3 + H_2S \rightarrow 2Fe(OH)_2 + 2H_2O + S \quad (2)$$

$$2Fe(OH)_2 + 2H_2 \rightarrow S2FeS + 4H_2O \quad (3)$$

$$4FeS + 3O_2 + 6H_2O \rightarrow 4Fe(OH)_3 + 4S \quad (4)$$

A heat exchanger is used for biogas drying. Another major deterrent to the use of SOFCs is that they can produce siloxane [$H(OSiH_2)nOH$], which is oxidized to form silicon oxide at high temperatures (Equation (5)). This creates glassy deposits on equipment surfaces and obstructs biogas supplementation.

$$H(OSiH_2)nOH + nO_2 \rightarrow nSiO_2 + (n+1)H_2O \quad (5)$$

Accordingly, the proposed system includes activated-carbon adsorption filters whose mesoporous structures can remove siloxanes and other contaminants. As briefly noted above, the biofuel produced by the BGT subsystem is then utilized by the SOFC power generators [21]. The high-quality waste heat from SOFCs is recovered by absorption chillers and a hot water generator [20]. This allows systemic-energy and hot water demand to be self-fulfilled.

Two operating modes are provided to cope with China's wide seasonal temperature variations. Switching between them is automatic, though they can also be manually overridden. In summer, absorption chillers are used for cooling the building [22]. To enhance the integrated system's energy efficiency, it incorporates a double-effect absorption cooling unit consisting of a pair of generators, one condenser, one absorber, a pair of heat exchangers and pairs of valves. The gas from SOFC servers is let into the flow controller to maintain a suitable temperature of between 500 °C and 550 °C. Then, the high-temperature gas is let into the generators for heat exchange. However, tri-effect absorption chillers with better coefficient of performance (COP) statistics can also be adopted to further improve energy efficiency. The low-quality waste heat within the coolers' exhaust gas can also be recycled for water heating. Alternatively, the cogeneration mode can be employed in other seasons. In that mode, the waste heat from the SOFC servers is directly recycled for water heating.

3. Economic Analysis

Five indicators have been adopted to assess the proposed system's economic performance and the economic feasibility of its application to buildings. These are *Income (USD)*, *CAPEX (capital expenditure, USD)*, *OPEX (Operating Expenditure, USD)*, *PP (Payback Period)*, and *IRR (Internal Rate of Return)*. Two equations (Equations (6) and (7)) are employed, where we assume the interest rate is 5% p.a. based on market expectations in the short-term. The assumption about the interest rate is derived from US 10-year government bond yields, which imply that an average level of interest rate is around 5% (4.7%) in the current year.

$$\text{CAPEX} = \sum_{t=1}^{pp} (income_t - OPEX_t) \quad (6)$$

$$0 = \sum_{t=1}^{N} \frac{Income_t - OPEX_t}{(1+IRR)^t} \quad (7)$$

Financial risk was then analyzed with single-factor sensitivity, for factors including initial system investment, operating/maintenance costs, fertilizer prices, electricity prices, and government subsidies. The economic feasibility of the proposed system was assessed via CAPEX and OPEX analysis, Operating Savings Analysis, and Payback Analysis. The version of the system with the most competitive payback was then considered further in light of these five and four additional factors' potential influence on single-factor changes.

3.1. CAPEX and OPEX Analysis

According to the Germany Information and Advisory Service on Appropriate Technology (ISAT), the initial cost of the BGT subsystem was estimated as $300,000, and that of two SOFC servers as $1.8 million. The initial cost of one-stage chiller products is $92,000 according to [23], while the two-stage chiller products are slighter higher (30%). Thus, the SOFC subsystem's initial costs including LiBr–H_2O absorption central air conditioning is $120,000, in addition to a water-heating unit ($100,000) [11]. Furthermore, the costs of auxiliary components (e.g., transformers, exhaust-flow controllers, etc.) were estimated at 5% of the main equipment cost, i.e., $101,000, as the maintenance cost in China is relatively lower than that in some developed countries [19]. Therefore, the estimated total cost of SOFC-based subsystem was $2.121 million, and of the integrated system, $2.436 million.

In China, DER and DWT facilities with high energy efficiency are encouraged, and their owners can obtain sustained funding, even up to 100%. More specifically, Shanghai's local government provides funds for green buildings at the rate of $500 per kW of reduction in energy use per year. Real-world applications of the proposed system would also be eligible for funding from schemes offered by both the Ministry of Science and Technology and the Ministry of Environmental Protection in China. Thus, a plausible subsidy of 60% was adopted for purposes of the present case study. It should also be noted here that the operating cost of the BGT subsystem was estimated to include labor costs of $2.10 per ton of biogas, auxiliary materials costs of $0.05 per 100 m^3 of biogas capacity, and maintenance and other ongoing costs of $2000 per year. Based on a reasonable daily production of biogas, then, the monthly operating cost for BGT would be $2900; and the monthly maintenance cost of the multi-generation subsystem, at 2% of initial system cost, would be $19,368. Thus, the total CAPEX of the proposed system is $2.421 M and its monthly OPEX is $19,368. After deduction of the 60% government subsidy ($168.6 k), the CAPEX would fall to $968,800.

3.2. System Operation Savings Analysis

In Shanghai, daily commercial electricity tariffs are divided into three types: on-peak (8 h in summer and 6 h in other seasons); normal (8 h in summers and 10 h in other seasons); and off-peak (the 8 remaining hours). In summer, therefore, there are approximately 240 peak hours, 240 normal hours and 240 off-peak hours per month, while in a month at any other time of year there are roughly 180 peak hours, 300 normal hours and 240 off-peak hours. The proposed system's two ES-5710 servers generate 360 MWh of electricity monthly. In summer, when it switches to tri-generation mode, the cooling capacity of LG WCSH012 is 422 kW, and COP is 1.57. Therefore, the monthly energy consumption of an electrical chiller with COP of 3.0 (140.7 kW) is 101,280 kWh. As the rate of work of the WCSH012 absorption chiller is 5.28 kW, the monthly electricity loss due to the cooling process is 3801 kWh. Therefore, the total monthly energy savings associated with the use of the absorption chiller is estimated as 97,479 kWh.

The exhaust flow rate, meanwhile, is 415 kg/h, with specific heat capacity estimated at 2.8 kJ/(kg K); the temperature change of exhaust as 110 K (160 °C to 50 °C); and the temperature change of the water as 15 K (30 °C to 45 °C). Thus, the basic monthly energy savings associated with use of the proposed water-heating method is 25,564 kWh. However, the waste heat in the exhaust gas is also recycled for water heating. Assuming a recycling efficiency of 80%, the overall monthly savings attributable to the water-heating system would be 263,520 kWh. The price of solid-waste fertilizer is estimated $72 per ton [24]. Thus, if a building's production rate of such fertilizer were

$52 tons/month, the monthly cost savings achieved by the proposed system's BGT subsystem would be $257,134. Therefore, the decrease in annual costs of the proposed system is expected to be $1,263,858, and the decrease in average monthly costs, $105,322.

3.3. Payback Analysis and Risk Analysis

The prices used for CAPEX and OPEX analysis are shown in Table 1. The PP of the proposed system is 36.46 months in the absence of any subsidy.

Table 1. Payback analysis.

Item	Total Price (USD)
CAPEX	
Biogas Generation System	$190,000
Biogas Treatment System	$110,000
Power Generation System	$1,840,000
Waste Heat Recycling	$281,000
Initial Cost at Gov. Subsidy of 60%	$968,800
OPEX	
Biogas Production Plant	$2900/month
Maintenance Cost	$19,368/month
Payback Period (without any subsidy)	36.46 months

Feasibility analysis of the proposed system first requires a calculation of financial risk. The above-mentioned single-factor sensitivity analysis considering nine factors was conducted using a variation range of ±10% and the analysis baseline of 11.22 months. In this range, the PP was sensitive to changes in government subsidy, SOFC servers' initial prices, and the whole-year electricity rate, though the subsidy was the most significant of all nine factors. The influence of PP from the CAPEX on Waste Heat Recycling (WHR) and BGT was not significant. As shown in Table 2, the PP's variation range under the various examined conditions was from a minimum of 9.23 months to a maximum of 13.35 months.

Table 2. Summary of single-factor sensitivity analysis.

	10%		−10%	
	Payback (m)	**Changes**	**Payback (m)**	**Changes**
Level of Gov. Subsidy	9.23	−17.76%	13.35	19.01%
Cost of SOFC Servers	12.28	9.42%	10.19	−9.19%
Elec. Rate (Whole Year)	10.25	−8.67%	12.39	10.39%
Elec. Rate (Non-summer)	10.43	−6.94%	12.12	8.07%
Fertilizer Price	10.87	−3.03%	11.58	3.24%
Cost of O&M	11.52	2.61%	10.94	−2.56%
Elec. Rate (Summer)	11	−1.99%	11.45	1.98%
Cost of BGT System	11.39	1.48%	11.05	−1.55%
Cost of WHR System	11.38	1.43%	11.06	−1.41%

4. Environmental Analysis

Prior research has highlighted buildings' energy performance and greenhouse gas emissions [25–27], and the proposed system is intended to improve the former and reduce the latter over a building's whole life cycle. The lifespan of the proposed system is estimated as 15 years. As the multi-generation system is fueled by biogas derived from waste, no additional energy source is required to fuel the SOFC energy server. Thus, the energy saved by the SOFC servers is 360,000 kWh monthly, or 64.8 million kWh over their whole life cycle. In tri-generation mode, the monthly energy savings achieved by the absorption cooling process is 97,479 kWh (equating to nearly 4.4 million kWh over the system's whole life cycle), and the energy saved monthly on water heating is 25,564 kWh (1.15 million kWh for the whole life cycle). In co-generation mode, the energy saved monthly by the proposed system's water-heating process is 263,520 kWh, or nearly 35.6 million kWh over its whole life cycle.

The present researchers also compared the proposed system's anticipated GHG emissions against that of both traditional thermal power generation and natural-gas power generation. Assuming that generating efficiency is 35%, the standard energy resource consumption coefficient for thermal power generation is 0.374 kce/kWh; and a productivity rate of 3 kWh/m^3 of natural gas is adopted for natural-gas power generation. Under these conditions, the life cycle resource savings of the proposed SOFC power-generation subsystem is 24.2352 tce or 21.6 million Nm^3 natural gas. In tri-generation mode, the life cycle resource savings of the proposed cooling method are 1.64 million kce or 1.46 million Nm^3 CNG; and those of the heating method, 430,242 kce or 383,460 Nm^3 CNG. In the tri-generation working condition, the life cycle resource savings of the heating method are 13.3 million kce or 11.86 million Nm^3 CNG. The GHG emission conversion coefficients for coal are 2.46 kg–CO_2/kg, 0.026 kg–CH_4/kg, and 0.0389 kg–N_2O/kg, and those for natural gas are 2.09 kg–CO_2/kg, 0.0373 kg–CH_4/kg, and 0.00373 kg–N_2O/kg. Thus, the proposed system is expected save 6510 tons of CO_2, 68.6 tons of CH_4, and 122.7 tons of N_2O annually, or 97,663 tons of CO_2, 1029 tons of CH_4, and 1840 tons of N_2O over its whole life cycle.

In addition, the proposed system can further combine with BIM to better achieve energy efficiency performance of the buildings in China [28].

5. Social Analysis

An eight-question (Q1–8) written survey was administered to 100 stakeholders in each of five cities (Beijing, Hong Kong, Shanghai, Xi'an, and Zhengzhou) to gauge their attitudes to the proposed system. These cities were chosen as being representative of the country's five main regions, i.e., Northern, Southern, Eastern, Western, and Central China. Equal numbers of respondents were selected from each of four groups: mechanical and energy engineers; environmental scientists and workers in green industry; construction and real-estate professionals; and end-users. The members of all four groups received the same survey items, which covered their attitudes towards the current states of waste treatment, energy consumption, and the natural environment, along with factors of potential public concern regarding the commercialization of the proposed system. SPSS, which is a data analytic system, was employed for preliminary regression analysis of the responses, and a significance test was then conducted.

The results indicated that the respondents had a satisfactory level of environmental awareness. Nearly all of the respondents (93%) agreed or strongly agreed that urban waste from buildings had huge environmental impacts (Q1). However, they were not confident in China's current waste-treatment methods, with 59% characterizing these as ineffective (Q2). In terms of their opinions of DWT and DER systems for buildings, 55% of respondents agreed or strongly agreed that DWT was effective at improving waste recycling and treatment in China (Q3), and the value of RII for significance was 0.732. A regression analysis of the responses to Q4 indicated that the respondents' attitudes towards the application of DWT systems to buildings were significantly dependent on the convenience of waste collection, the performance of waste separation, the level of environmental pollution, GHG emission levels, wastage of resources, and waste-treatment costs.

Most (87%) of the respondents expressed a belief that DER systems could improve buildings' integrated energy efficiency (Q7), and the value of RII for significance was 0.824. Regression analysis conducted on the responses to Q8 found that stakeholders' opinions on applications of DER to buildings depended significantly on energy efficiency, energy waste, individual environmental awareness, energy costs, initial equipment costs, and GHG emissions. Therefore, it would appear that the four surveyed stakeholder groups hold positive attitudes to building applications of both DER and DWT. The respondents were also encouraged to provide open-ended comments about the proposed system, and these showed that their main concerns were that it would perform poorly in an economic sense and create financial risks. The proposed system's major advantages and drawbacks, as reported by the respondents, are summarized in Table 3.

Table 3. Stakeholder-reported pros and cons of the proposed system.

Advantages	Disadvantages
Less greenhouse gas emissions	High space requirements
Less energy waste	High initial cost
Less fossil-fuel consumption	High O&M Cost
Less waste-treatment time	Long payback period
Less environmental pollution	High financial risk
Easier waste collection	Poor energy performance
Less LCC (life cycle cost)	

6. Conclusions

The proposed SOFC-based biogas-from-waste multi-generation system for buildings, which features simultaneous production of biogas, electricity, air-conditioning and hot water, represents an innovative new possibility for the commercial use of SOFC in China. Its estimated economic, environmental and social performance were all found to be satisfactory. With regard to the first, the proposed system's annual financial savings of more than $1.25 million gives it a short payback period (<12 months) and satisfactory resistance to financial risks. With regard to the second, it can achieve markedly higher energy efficiency (i.e., 85%) than conventional combustion power generators, while significantly reducing GHG emissions. Finally, in relation to the third, a geographically diverse group of stakeholders, including experts in various relevant fields, was found to hold positive attitudes towards the application of the proposed system, expressing concerns mostly about its economic performance and financial risks. With foreseeable technological advancements potentially offering this integrated SOFC multi-generation system even greater flexibility while reducing its space requirements, it is anticipated that the proposed application can appropriately serve future infrastructure and building projects in China and beyond.

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